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火山岩储层地质研究回顾

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摘要：火山岩油气藏广泛分布于全球13国家的40余个盆地中，是油气勘探的重要领域之一。经过近20年的积累，火山岩储层研究取得了丰富的成果，已成为研究的热点。研究结果表明，火山岩发育11类28型孔隙，其中原生气孔、炸裂缝和冷凝收缩缝等为特有的类型，原生孔缝与次生孔缝的组合形成优质储层；盆地内火山岩多属于中—低孔、中—低渗储层，局部可发育高孔、中—高渗储层；火山岩的孔隙度和渗透率随埋深的增大而减少，通常在3 km之上（沉）火山碎屑岩的孔隙度和渗透率高于熔岩类，在3 km之下则相反；总体来看各类岩性均可发育有利储层，但在具体的区块中只能有特定的岩性发育有利储层；岩相中有5相7亚相可成为有利相带；储层分布模式受火山地层单元约束，如熔岩流垛叶体和熔岩穹丘形成“上好下差”的模式，熔岩流储层物性高于熔岩穹丘；火山机构的中心相带储层物性好于近源相带、远源相带最差。多数有利储层分布在喷发间断不整合界面或构造不整合界面之下的200 m范围之内。盆地火山岩储层是多种成岩作用的综合叠加结果，具有复杂的形成过程，特别是火山地层经受了多次抬升和埋藏时其储层演化过程更加复杂。其中挥发分逸出、冷凝收缩、埋藏前风化、脱玻化作用等是火山岩储层特有的储层成因类型，高含量的酸性条件下易溶成分为溶蚀/溶解提供了物质基础。火山岩储层特征和分布规律研究基本达到定量阶段、而储层形成机理研究还处于定性阶段，基于火山地层单元的储层建模和孔隙成因量化研究应该是下一步研究的重点内容。

关键词：火山岩储层；火山岩油气藏；储层分布规律；储层成因；控制因素
中图分类号：TE122.2 **文献标识码**：A

Review of volcanic reservoir geology

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Abstract: Volcanic oil and gas reservoirs are widely distributed in more than 40 basins in 13 countries around the world, and are one of the important areas of hydrocarbon exploration. After nearly 20 years of accumulation, the research on volcanic reservoirs has achieved great results and become a research hotspot. The research results show that there are 11 classes including 28 types of pores in volcanic rocks, among which primary gas pores, explosive fractures and condensation shrinkage joints are unique types. The combination of primary pores and fractures and secondary pores and fractures forms high-quality reservoirs. Most of volcanic rocks in the basin are medium-low porosity and medium-low permeability reservoirs, and high- and medium-high permeability reservoirs are developed in local area. The porosity and permeability of volcanic rocks decrease with the increase of burial depth. Usually above 3 km, the porosity and permeability of (sed) volcanic pyroclastic rocks are higher than those of lavas, and the opposite is true below 3 km. Generally speaking, various lithologies can develop favorable reservoirs, but in specific blocks, only specific lithologies can develop favorable reservoirs. There are 5 lithofacies and 7 sub-lithofacies which can become favorable facies zones. The distribution mode of reservoirs is restricted by the volcanic stratigraphic unit. For example, lava flow lobe and lava dome form a pattern of “good in upper layers and poor in lower layers”. The physical properties of lava flow reservoirs are superior to those of lava dome. The physical properties of reservoirs in the central facies zone of the volcanic edifice are better than those of the proximal facies zone, and those of the distal facies zone are the worst. Most favorable reservoirs are distributed within 200 m below the eruptive interval unconformity boundary or tectonic unconformity boundary. The volcanic reservoir in the basin is the product of comprehensive multi-diagenesis superposition, and has a complicated formation process. Especially, when the volcanic strata have undergone multiple times of uplifting and burial,

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the evolution process of the reservoir is more complicated. In this process, escape of volatile components, condensing shrinkage, weathering before burial, and devitrification present the unique genesis types of volcanic reservoirs. The soluble components under acidic conditions provide the material basis for alteration/dissolution. The research of the characteristics and distribution laws of volcanic reservoir has basically reached the quantitative stage, while that of reservoir forming mechanism is still in the qualitative stage. Quantitative research of reservoir modeling and pore genesis based on volcanic stratigraphic units should be the focus of the next step.

Key words: volcanic reservoir; volcanic oil and gas reservoir; distribution pattern of reservoir; reservoir genesis; controlling factor

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1　火山岩油气藏分布及储层研究现状

在全球 50 多个国家/地区的 300 余个盆地/区块内发现了火成岩油气藏或在火成岩层段发现油气显示[1-5]，其中在 13 个国家的 40 个盆地内的火山岩中获得了工业性油气流和大规模的储量。近年来，在中国多个盆地的火山岩中也发现了高产油气藏[6-10]，证实了火山岩储层的良好含烃能力。火山岩油气藏已成为全球油气资源勘探开发的重要领域[11-15]。从分布范围来看，在环太平洋构造域的比例较高（图 1）。从时代属性来看，全球火山岩油气藏多集中在中生代—新生代（约占 70%），古生代次之[16-19]。

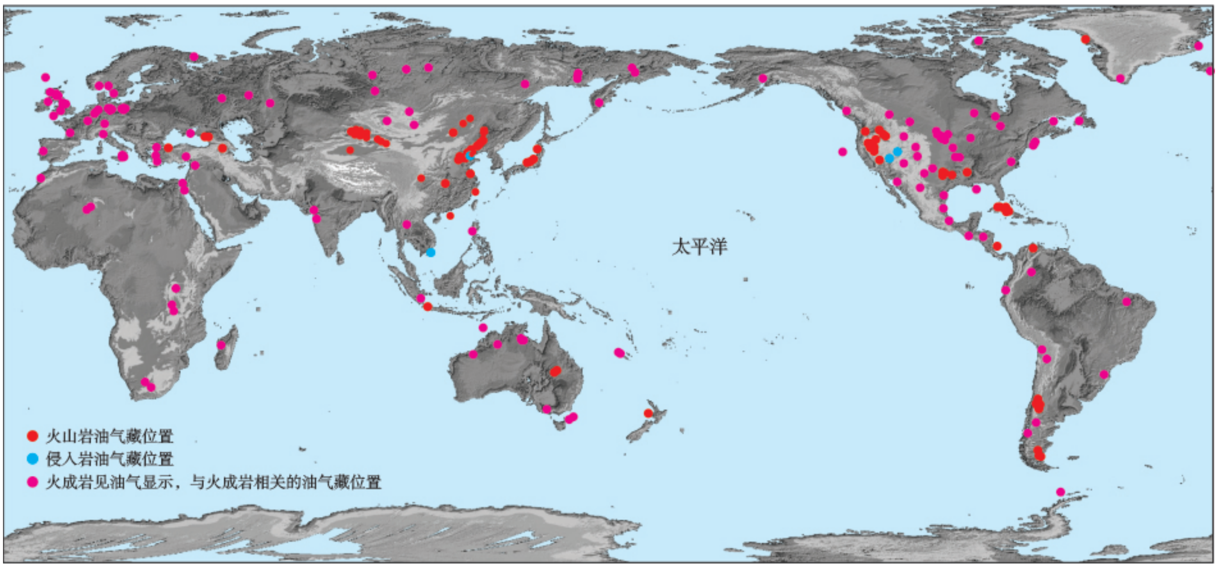


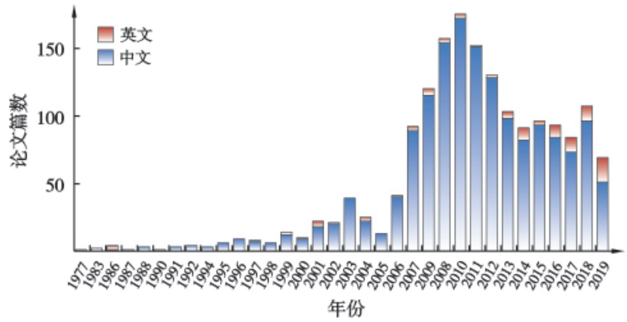
图 1　全球火成岩油气藏、油气显示及与火成岩相关的油气藏分布（据文献[3，5，7，9]整理）

Fig. 1　Distribution of location of the oil & gas reservoirs and oil show in the igneous rocks and the hydrocarbon associated to the igneous rocks

从勘探发现来看，中国已成为全球火山岩油气藏勘探实践的主体[20-23]；从论文发表数量来看，也产出了大量有关火山岩油气藏的科研成果，中国已成为全球火山岩油气藏勘探实践和理论创新的主体，特别是在 2007 年之后呈现出快速发展趋势（图 2）。一个区块火山岩油气藏的勘探历程整体上可划分为 4 个阶段。如在松辽盆地分别为：①兼探发现阶段（1985 年之前）；②有针对性的探索阶段（1985—2000 年）；③勘探重大突破阶段（2000—2004 年）；④勘探大发展阶段（2004 年至今）[24]。其他区块的火山岩勘探也具有相似的经历，只是在时间节点上存在差别[25]。

火山岩油气藏研究的重要组成部分包括储层特征、分布模式、形成机理和控制因素等[26-29]。火山岩储层有其特殊之处，如发育原生的气孔和裂缝、在酸性条件下易溶成分含量高有利于形成次生孔隙、遭受埋藏前风化淋滤作用的改造等；甚至沉积岩中火山物质成分的存在有利于阻止粒间孔被硅质充填、促进孔隙的保存等[30-31]。为了系统分析火山岩储层的特殊之处和研究进展，笔者将火山岩储层地质研究成果分为储集空间类型、物性特征、分布规律和形成机理 4 个方面进

行了总结讨论，分析了火山岩储层的研究程度、明确了下一步研究的方向。希望能起到抛砖引玉的作用，引起学者们进一步对火山岩储层地质理论深入研究。



注：中文文献查询自中国知网数据库，分别使用关键词“火山岩＋储层”、“火山岩＋油气藏-储层”、“火山岩＋气藏-储层”、“火山机构＋盆地”、“火山地层＋盆地”进行检索，共查询到 1602 篇论文；英文文献查询自 web of science 数据库，分别使用关键词“volcanic＋reservoirs”、“volcanic rocks＋basin”、“volcano stratigraphy”进行检索，共查询到 103 篇论文。

图 2 与火山岩储层相关的论文情况

Fig. 2 Related publication about the volcanic reservoirs

2 储集空间

2.1 类 型

依据形成过程和几何特征，可将储集空间划分为原生孔隙和裂缝、次生孔隙和裂缝[32-34]。笔者依据储集空间的成因和分布特征，将其划分为 11 类 28 型，其中，原生孔 3 类 5 型、原生缝 2 类 9 型、次生孔 3 类 8 型和次生缝 3 类 6 型(表 1 和图 3)。原生孔隙以颗粒间孔和气孔(包括石泡空腔孔、杏仁体内孔等)为主，次生孔隙以铸模孔、筛状孔和晶间微孔等为主；原生裂缝可见冷凝收缩缝(包括淬火缝、柱状节理、层状冷凝缝、似缝合线、宏观龟裂缝和微观龟裂缝等)、炸裂缝(矿物内和岩屑内炸裂缝)、隐爆缝(部分缝可能形成于后期岩浆活动)和自碎缝(熔浆流动-固化过程中由流速差异导致其自碎化)，次生缝可见构造缝和风化缝、溶蚀缝等。构造缝与应力性质相关，在张性环境时可产生网状的裂缝，在压性环境下可产生高角度共轭裂缝；风化缝中常见层节理和球状风化缝；溶蚀缝可在任意裂缝的基础上产生。当原生孔隙叠加次生孔隙时、增加了孔隙类型识别的难度；同样地，原生和次生裂缝可叠加溶蚀充填作用，使裂缝的形态复杂化。

研究表明，火山岩的原生孔隙与岩相密切相关[35-38]，喷溢相上部亚相以气孔、石泡、杏仁等原生孔隙为主，喷溢相下部亚相以冷凝收缩缝为主，水下喷发的熔岩发育丰富的淬火缝[39]；爆发相热碎屑流亚相发育丰富的粒间孔，侵出相发育丰富的裂缝[40]。次生孔隙受风化、埋藏溶蚀/溶解、构造和脱玻化等作用影响[41-45]，其中，前 3 种作用与原生孔隙和裂缝形成的连通网络相关。

2.2 组合特征

从发现的火山岩油气藏来看，储集空间类型基本为原生孔缝与次生孔缝的组合，由于孔缝类型多样，其形成的储集空间组合类型也十分复杂，不同盆地/区块间也各不相同。如松辽盆地白垩系营城组有气孔-溶蚀孔-裂缝型、气孔-裂缝型、粒间孔-溶孔-裂缝型和粒内孔-溶孔-裂缝型[46-48]；其中，以气孔-溶蚀孔-构造裂缝组合的物性较好[49]。准噶尔盆地火山岩常见构造缝-溶蚀缝-溶蚀孔、原生气孔-构造缝-溶蚀缝-溶蚀孔、晶间孔-溶蚀孔和裂缝型 4 种组合[50-54]。三塘湖盆地火山岩常见原生气孔-溶蚀孔组合、构造缝-溶蚀缝-自碎缝组合两类[55-56]。辽河盆地东部凹陷新生界火山岩储层有裂缝型、裂缝-孔隙型、风化-淋滤孔缝型[57]。渤海湾盆地发育孔隙-气孔型和裂缝型两类[58]，部分层段的裂缝对储集空间的贡献可达 90％[59]。

不同的储集空间类型组合对储层物性特征有显著的影响，如松辽盆地东南缘 Y1D1 井和 Y3D1 井揭示裂缝型储层的渗透率随孔隙度增加而快速增大；气孔-裂缝型储层的渗透率随孔隙度增加而增大的斜率较小；粒间孔-裂缝型储层的渗透率随孔隙度增加而增大的斜率中等[60]。通过对比中国火山岩储层的储集空间可知，东部盆地以原生型为主、西部盆地以改造叠加型为主[61]。

3 储层物性特征

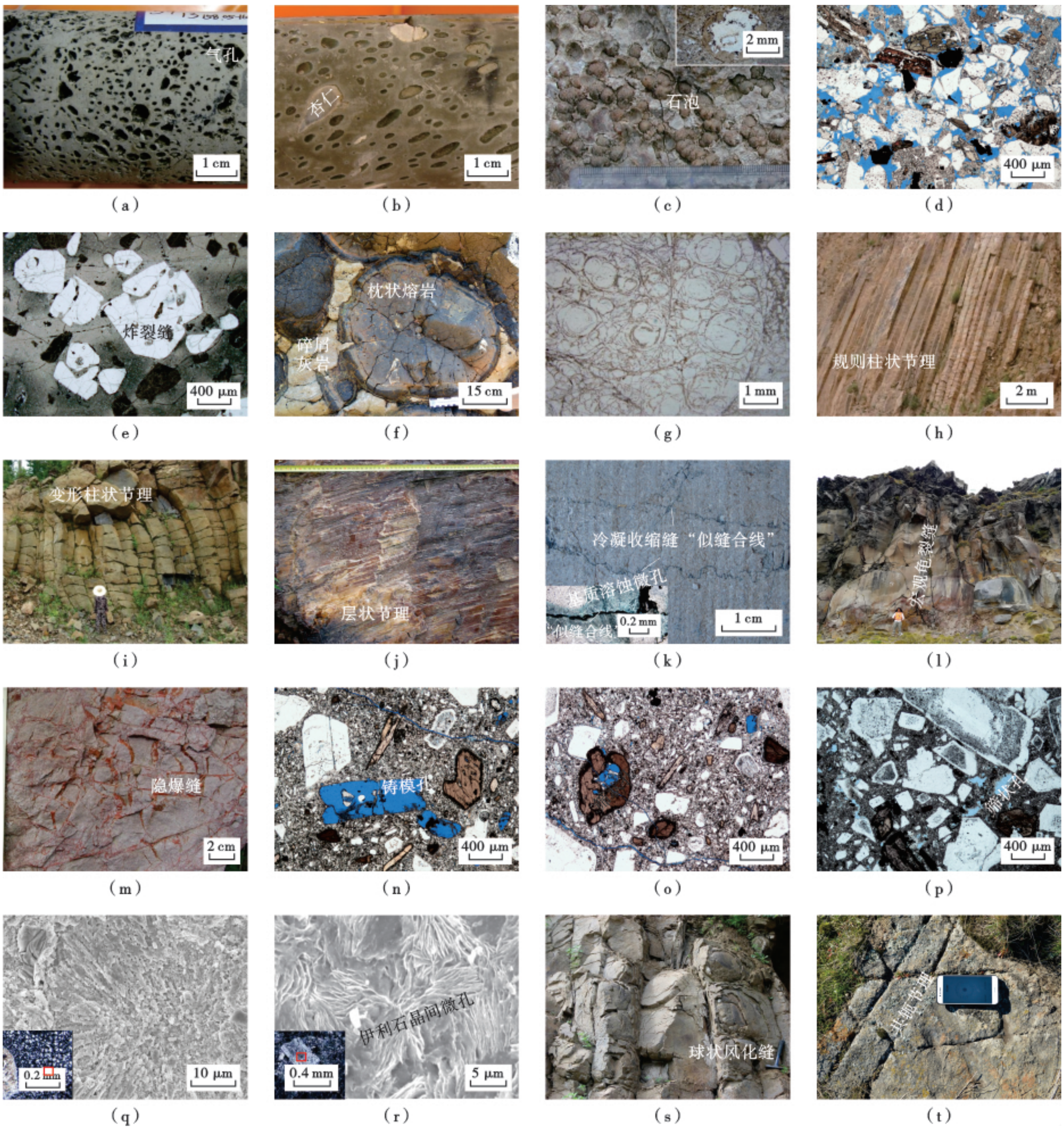
各个盆地/区块的储层物性变化较大，同一盆地/区块间的储层物性变化也很大(图 4)。火山岩属于中—低孔、中—低渗、小孔喉储层，局部可发育高孔、中—高渗储层；在一些盆地内也称作致密储层[62-65]，火山岩储层的非均质性强，这与岩石组构、岩石的矿物成分以及孔隙结构密切相关[66-68]；平均喉道半径与渗透率有很好的相关关系，火山岩孔喉比大、束缚水饱和度高、存在启动压力梯度[69]。火山岩储层物性下限较低，如新疆克拉玛依九区凝灰岩类孔隙度下限为 5.0％、熔岩类孔隙度下限为 4.5％，均低于相同层位的沉积岩[70]，说明火山岩作为有效储层具有良好潜力。

火山岩孔隙度、渗透率和孔喉随围压的增大而减小[71-72]，当围压撤去时渗透率不能恢复到原始值[73]。初始孔隙度大的样品随围压增大、孔隙度和渗透率减少的量越大[74]。当孔隙度小于 20％时，随着孔隙度变大，其产生裂缝的门槛压力迅速变小；孔隙度大于 20％时

表 1　火山岩储集空间类型划分方案

Table 1　Classification of reservoir space in volcanic rocks

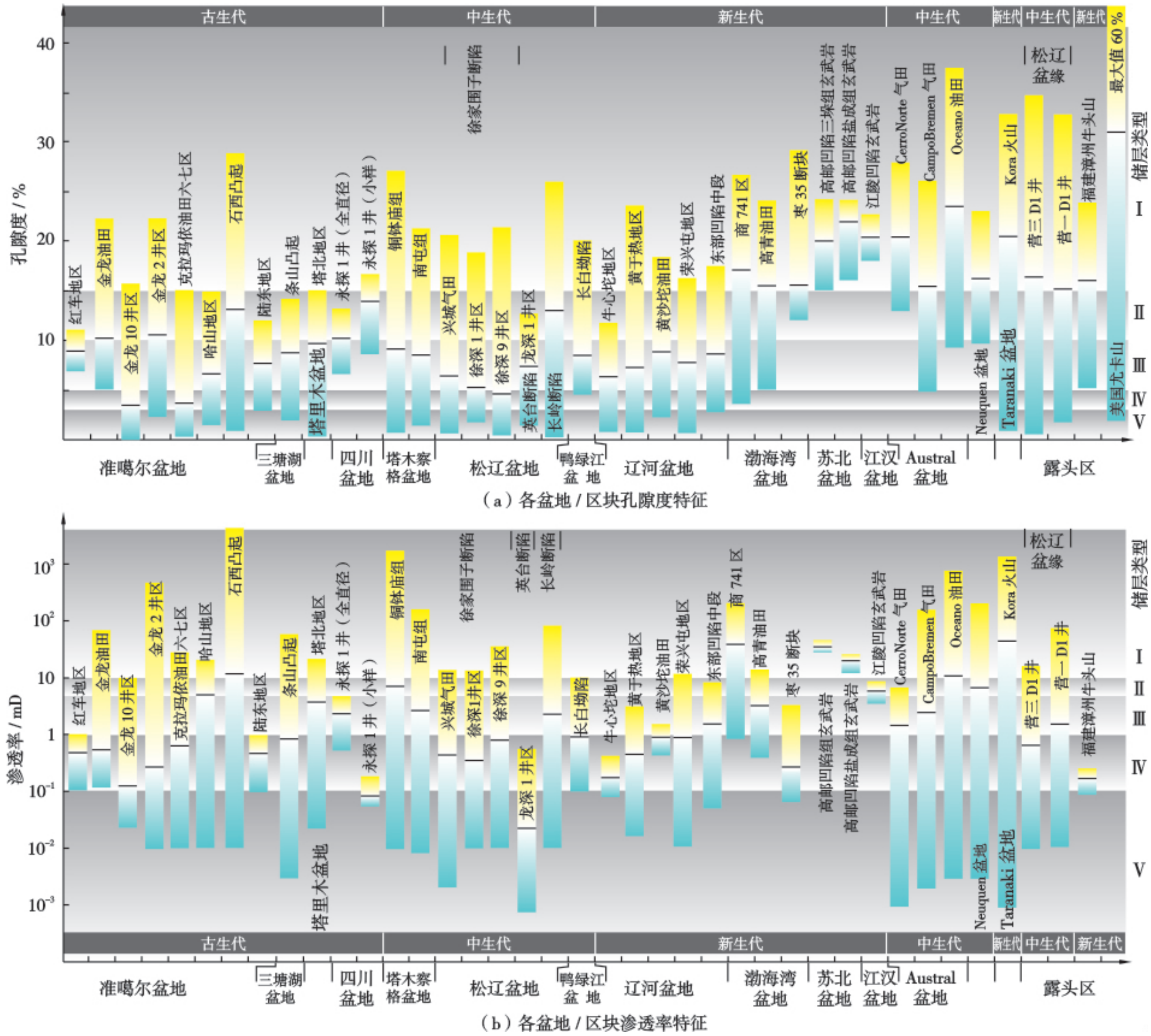
形成阶段	形态	类	型	成因	特征	分布
原生	孔隙	气孔类	气孔	熔浆中含有的挥发分(水、二氧化碳、氟和氯等组分)随着岩浆上升时的减压过程发生脱气作用产生气泡,在喷发到地表冷却过程被岩石固定成气泡形成	形态以圆球形和椭球形为主、见管状,直径差异大,呈线状定向分布或离散分布。连通率与气孔的孔隙度、裂缝发育程度呈正相关	流纹质/安山质/玄武质简单—辫状熔岩流顶部常见,面孔率可以随与喷出口的距离增大而减少
			石泡空腔孔	富含挥发分的熔浆在固结时气体逸出膨胀而产生空腔,空腔壁为多层同心放射状纤维钾长石或长英质组成	形态为圆球形或椭球形,直径为数厘米。沿孔壁产生冷凝收缩缝隙,连通性可能好	流纹质简单熔岩流顶部常见
			杏仁体内孔	具有气孔构造的岩石,其气孔被矿物质(如方解石、石英、玉髓等)所充填形成的一种形似杏仁状的构造	杏仁体中部未充填部分的残余孔隙和充填物之间的晶间微孔,形态多样	玄武质/安山质简单—辫状熔岩流顶部常见
		颗粒间孔		由于火山碎屑颗粒(常为岩屑和晶屑)支撑搭成格架、且未被杂基和胶结物完全充填而保存的孔隙	形态不规则,通常沿碎屑边缘分布,连通性较好	热碎屑流、热基浪、水下火山碎屑、再搬运火山碎屑堆积中常见
		熔蚀孔		地下深处岩浆携带高温的石英、长石上升至浅部或喷出地表时,由于矿物熔点随静压力降低而降低,斑晶部分被熔化而形成孔隙	港湾状、浑圆状、筛孔状,连通性差	斑状结构岩石中的斑晶,凝灰熔岩中的晶屑
	裂缝	冷凝收缩缝	淬火缝	熔浆喷出时与水体接触,熔浆发生淬火而快速冷却形成裂缝	呈放射状和环状,连通性好	水下喷发的熔岩流中常见,如枕状熔岩和玻璃质熔岩
			柱状节理	由于熔浆黏度或地形的原因,使熔浆不易流动或不流动的情况下缓慢冷却,熔浆沿着冷却中心固结,由于外部先行固结而导致内部熔浆近似等体积固结而产生缝隙	根据柱体直径、方向和截面多边形是否稳定可分为规则和不规则两类,截面多边形为三角形—八边形、边长为几厘米至几十厘米,连通性极好	见于各类熔岩穹丘,各种简单熔岩流的中—下部
			层状冷凝缝	熔浆在流动过程中,由于冷却作用导致熔岩流外部的流动速度低于内部流动速度产生的剪切力,而形成与流动方向平行的裂缝	呈层状或片状,水平方向连通性好	通常在简单熔岩流底部
			似缝合线冷凝缝	熔浆在流动过程中,塑性表壳在流动过程中发生流变作用而产生揉皱,从而形成微观缝隙	呈齿状,连续性差,连通性差	少见,分布于熔岩流顶、底部
			宏观龟裂缝	熔浆在流动的后期阶段,熔浆供应量减少,熔浆以等容冷却作用为主,叠加重力的牵引,而形成与流动方向垂直的宏观裂缝	截面为不规则多边形、具有规则—不规则缝面,垂直方向连通性好	在各种简单熔岩流中,可贯穿整个熔岩流
			微观龟裂缝	岩浆喷发流动时,其表层存在近似等体积、中等冷却速度时形成	不规则状微裂缝,连通性中等,但分布局限	见于各种熔岩流顶、底部的几厘米至几十厘米的范围内
		炸裂缝	失压炸裂缝	熔浆在上升过程中压力降低而膨胀的过程,使矿物破碎成缝	晶面不规则状或似解理状	含斑晶的熔岩或含晶屑的火山碎屑岩中
			爆发炸裂缝	由于熔浆中的挥发分逸出,但气泡膨胀受阻,其膨胀力高于基岩骨架的拉伸强度而发生炸裂,在岩屑或矿物中保存下来的裂缝	火山碎屑内的炸裂缝,连通性好	火山碎屑岩中
			隐爆缝	在浅成或超浅成环境中,在岩浆顶部围岩经受压力大于岩石爆破应力条件下,所发生炸裂作用而形成的裂缝	树杈状、网状,常充填岩汁,当充填程度低时具有较高的孔隙度和渗透率	常见于中酸性火山机构的火山通道附近
次生	孔隙	溶蚀孔	铸模孔	岩石中的矿物(辉石、角闪石和长石等)被完全溶解产生的孔隙	孔隙形态规则,保留原晶体假象,连通性较好,溶蚀/溶解作用中等	原生裂缝发育的岩石中常见
			筛状孔	岩石中的矿物(辉石、角闪石和长石等)部分区域被溶解产生的孔隙	细小的筛孔状,具有一定的连通性,溶蚀/溶解作用中等	原生裂缝发育的熔岩和原生孔隙发育的火山碎屑岩中常见
			洞穴状孔	岩石中的基质被溶解产生的孔隙	较大的孔径,具有较好的连通性,溶蚀/溶解作用强	原生孔隙发育的火山碎屑岩中常见
			晶内微孔	岩石中的矿物(辉石、角闪石和长石等)被部分溶蚀产生的微孔隙	细小的海绵状孔,具有一定的连通性,溶蚀/溶解作用弱	原生裂缝发育的熔岩和原生孔隙发育的火山碎屑岩中常见
			基质海绵状溶蚀孔	岩石中的基质被部分溶蚀产生	细小的海绵状孔,具有一定的连通性,溶蚀/溶解作用弱	原生孔隙发育的火山碎屑岩中常见
		重结晶微孔	脱玻化微孔	岩石中的玻璃质成分脱玻化形成	细小的海绵状孔,具有一定的连通性,代表温度和压力升高	玻屑/浆屑含量高和玻璃质岩石中常见
		断层角砾岩中角砾间孔		构造裂隙充填的断层角砾之间的孔隙	随断层角砾呈不规则状,主要为粒间孔,连通性好	断裂带中常见
	裂缝	风化缝	层状风化缝	深埋藏致密块状火山岩抬升出露地表时,由于载荷力的卸载,表层岩石膨胀而产生的层状裂缝	在地表沿地形延伸,向深部缝间距变大	在风化壳顶部
			应力释放缝	深埋藏胶结程度差的火山碎屑岩,在抬升出露地表时,由于载荷力的卸载在颗粒内和颗粒边缘产生的微裂缝	方向不定,形状多样	在风化壳顶部
			球状风化缝	通常由≥ 3组方向的节理将岩石切割成多面体的小块,小岩石块的边缘和隅角从多个方向受到风化(温度及水溶液等因素)作用而最先破坏,向内部变弱,由于风化强度差异形成圈层,导致裂缝形成	同心圆状、椭圆状	在风化壳顶部,经受构造改造的块状熔岩,柱状节理发育的熔岩更容易产生
		构造缝	剪切构造缝	火山岩成岩后遭受剪切应力作用产生的裂缝	高角度、缝面平直的裂缝	致密的熔岩、碎屑熔岩和火山碎屑岩中均可以发育
			张性构造缝	火山岩成岩后在张性构造应力下岩石发生破碎	网状、不规则、连通性好	致密的熔岩、碎屑熔岩和火山碎屑岩中均可以发育
		溶蚀缝		上述各类裂缝在大气水、地层流体等的作用下发生溶蚀/溶解作用,使原来的裂缝扩大	在已有的形态基础上可改造为多样的形态	原生缝和构造缝发育,与流体通道沟通的区域常见



(a)玄武岩、气孔构造,吉林省九台地区营三 D1 井 161.05 m,下白垩统营城组;(b)玄武岩、杏仁体残余孔,吉林省九台地区营三 D1 井 113.85 m,下白垩统营城组;(c)流纹岩、石泡空腔孔,吉林省六台乡石场村采石场,下白垩统营城组;(d)晶屑凝灰岩,发育粒间孔、叠加溶蚀筛状孔,新西兰 Taranaki 盆地 Kora-1 井 112.86 m,中新统 Manganui 组;(e)熔结凝灰岩,石英发育炸裂缝,徐家围子断陷徐深 1 井 3 528 m,下白垩统营城组;(f)枕状玄武岩,球枕边缘发育淬火缝、中部发育放射状环状节理,新西兰奥马鲁新生界 Waiareka 组;(g)珍珠岩、冷凝收缩缝,吉林省九台地区三台乡下白垩统营城组;(h)流纹岩、规则柱状节理,吉林省四平市山门镇下白垩统营城组;(i)玄武岩、变形柱状节理,吉林省漫江镇采石场更新统双峰期;(j)流纹岩、层状冷凝-剪切缝,吉林省四平市山门风景区下白垩统营城组;(k)英安岩,发育"似缝合线"冷凝收缩缝,德惠断陷 DS17 井 2 234.54 m,下白垩统营城组;(l)安山质熔岩、宏观龟裂缝,新西兰 Ruapehu 火山新近系 Whakapapa Iwikau 组;(m)隐爆缝,吉林省九台地区下白垩统营城组;(n)安山岩,角闪石斑晶被完全溶解产生铸模孔,新西兰 Taranaki 盆地 Kora-1a 井 1 894.12 m,中新统 Manganui 组;(o)安山岩,角闪石斑晶被溶解产生晶内筛状孔,新西兰 Taranaki 盆地 Kora-1a 井 1 894.12 m,中新统 Manganui 组;(p)凝灰类岩的基质溶蚀/溶解产生筛状孔,新西兰 Taranaki 盆地 Kora-1a 井 1 909.58 m,中新统 Manganui 组;(q)流纹岩,基质脱玻化形成球粒、发育晶间微孔,英台断陷龙深 201 井 3 603 m,下白垩统营城组;(r)流纹岩中碱性长石斑晶被溶蚀形成片状伊利石晶体间微孔,英台断陷龙深 301 井 3 046 m,下白垩统营城组;(s)柱状节理玄武岩发育球状风化缝,吉林省四平收费站渐新统大孤山组;(t)粗安岩发育共轭节理,新西兰基督城中新统 Lyttelton 火山。

图 3 火山岩储集空间类型特征和识别标志

Fig.3 Characteristics and identification mark of reservoir space in volcanic rocks



注：黄色、浅蓝色的长方形顶、底分别代表孔隙度和渗透率的最大值、最小值，黑色横线代表平均值。除 Taranaki 盆地资料，其他资料据文献[9，33，45，90-122]整理。孔隙度和渗透率分类标准据中华人民共和国石油行业标准 SY/T 6285—2011[123]。

图 4　火山岩储层孔隙度和渗透率特征

Fig. 4　Characteristics of porosity and permeability of volcanic rocks

产生裂缝的门槛压力没有明显下降[75]。对于以孔隙为主的样品，当围压升高时渗透性减少率小[76]；对于裂缝型储层裂缝越发育、应力敏感性越强，含水岩样的渗透率随有效压力增大而降低的幅度要大于干燥的岩样[77]；在低压段受压后裂缝产生闭合、渗透率下降较快，高压段下降速率减缓[78]。

储层评价需要根据储集空间类型及组合、储层物性和微观孔隙结构特征等参数综合起来才可能建立起与产能的合理关系[79-83]；而储层对比则应该在高精度地层格架的约束下进行研究[84-85]。对于岩石润湿性，其可能受原油的酸值控制，Amott 水指数随酸值的增加呈指数下降，从而影响油的流动性和采收率[86]。

4　储层分布规律

储层分布规律研究根据时间顺序可划分为两个阶段：①建立起储层与岩性、岩相、埋深的关系；②结合火山地层特征建立储层与地层单元、地层界面的关系。这两个阶段呈递进关系。

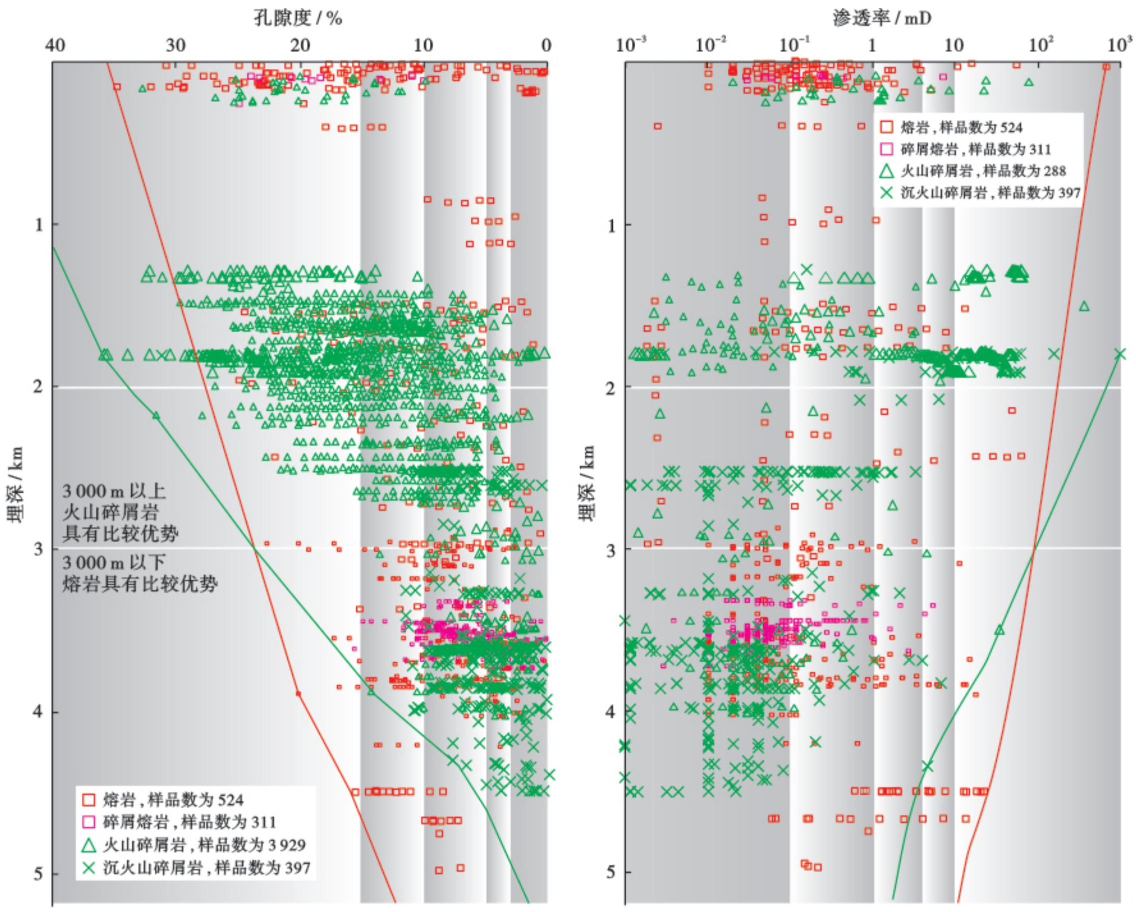
4.1　火山岩储层与埋深的关系

岩心实测结果表明，火山岩储层物性随着埋深的增加都具有减少的趋势（图 5），但在深层还有较多的原生孔隙能得到保存，可具有物性上的优势效果。其中，熔岩的孔隙度和渗透率随埋深增大的减少幅度小于火山碎屑岩和沉火山碎屑岩；熔岩的孔隙度、渗透率最大值在深部大于火山碎屑岩和沉火山碎屑岩；通常

埋深在 3 km 之上时火山碎屑岩和沉火山碎屑岩可具有较高的储层物性，埋深在 3 km 之下时熔岩仍可能有高孔隙带存在，具有相对好的优势[87]。塔木察格盆地和海拉尔盆地的火山碎屑岩在 1.4～2.8 km 的埋深范围内为有利储层[88]；火山碎屑岩和沉火山碎屑岩物性变化可能还与颗粒的直径大小相关；从沉火山碎屑岩来看，沉角砾/沉集块岩的物性变化幅度较沉凝灰岩小，所以相比之下沉角砾岩/沉集块岩在深层更具有优势[89]。

4.2 岩性与储层的关系

目前钻井揭示的火山岩种类丰富。根据成分可划分为基性、中性和酸性火山岩；根据成岩方式可划分为熔岩、碎屑熔岩和火山碎屑岩，其中，熔岩为冷凝固结成岩，火山碎屑岩为压实固结成岩，碎屑熔岩为过渡类型；各类岩石根据组构特征又可划分出细类[124]。从各区块揭示的情况来看，各种成分和成岩方式的火山岩均可发育储层；但在具体的区块中只能有特定的岩性成为有利岩性。流纹岩类在松辽盆地徐家围子断陷[125]和长岭断陷、渤海湾盆地南堡凹陷[126]、准噶尔盆地陆东—五彩湾地区[52]、阿根廷南部巴塔哥尼亚 Austral 盆地[33]等地区为有利岩性带。粗面岩类在松辽盆地徐家围子断陷[127]和王府断陷[128]、辽河盆地欧北—大湾地区[129]等地区为储层有利岩性带。玄武岩类在松辽盆地徐家围子断陷[130]和德惠断陷[131]、辽河盆地[106]、准噶尔盆地北三台[132]、三塘湖盆地牛东地区[56]等地区为有利岩性带。玻璃质熔岩在松辽盆地[124]和阿根廷 Austral 盆地 Oceano 油田[33]为有利岩性带。火山碎屑熔岩在四川盆地[9]、阿根廷 Austral 盆地 Campo Bremen 气田[33]为有利岩性带，且物性与熔结程度呈反比关系。角砾岩在渤海湾盆地临商地区[133]/南堡凹陷 5 号构造带[126]，准噶尔盆地克百地区[134]、哈山地区[120]、金龙油田[110]、克拉美丽气田[50]，新西兰 Kora 火山等地区为有利岩性带。凝灰岩在准噶尔盆地北三台地区[132]、克百地区[134]为有利岩性带。沉火山碎屑岩在准噶尔盆地陆西地区[135]、海拉尔盆地贝尔凹陷苏德尔特构造带[136]、松辽盆地英台断陷和王府断陷[89]为有利岩性带。



注：松辽盆地数据据文献[87，89]，塔木察格盆地数据据文献[88]，海拉尔盆地数据据文献[136]，三塘湖盆地数据据文献[56]，塔里木盆地数据据文献[105]，其他数据源于本文。熔岩样品源于松辽盆地（共 349 个）、三塘湖盆地（共 155 个）和塔里木盆地（共 20 个），碎屑熔岩样品源于松辽盆地（共 311 个），火山碎屑岩样品源于松辽盆地（共 94 个）、海拉尔盆地（共 3641 个）、三塘湖盆地（共 53 个）和新西兰（共 141 个），沉火山碎屑岩样品源于松辽盆地（共 357 个）、新西兰（共 40 个）。

图 5 火山岩储层与埋深的关系

Fig.5 Relationship between reservoir parameters and depth for volcanic rocks

4.3 岩相与储层的关系

钻井揭示火山岩储层与岩石的组构特征关系密切,如气孔-杏仁构造、枕状构造和球粒结构等组构发育的熔岩孔隙度较高,火山碎屑颗粒大小、排列方式和熔结结构等对火山碎屑(熔)岩的储层影响明显。岩石的组构可与岩相对应,所以有利岩相带的分析可进一步明确储层分布规律,可采用 5 相 15 亚相的分类方案,具体为火山通道相、爆发相、喷溢相、侵出相和火山沉积相[137]。通过岩相的识别及其与储层关系的分析可知,有火山通道相火山颈亚相、爆发相热碎屑流亚相/空落亚相、喷溢相上部亚相、侵出相内带亚相、火山沉积相含外碎屑火山沉积亚相共 5 相 7 亚相为有利相带。

喷溢相上部亚相在松辽盆地徐家围子断陷[137-138]和长岭断陷[139]、二连盆地洪浩尔舒特凹陷中生界火山岩[140]、准噶尔盆地西北缘地区[141-142]和陆西地区[135]等区域为有利岩相带。爆发相热碎屑流亚相在松辽盆地徐家围子断陷[124,143]和长岭断陷[139]、鸭绿江盆地长白坳陷[111]、准噶尔盆地西北缘[141-142]和陆西地区[135]为有利岩相带。爆发相热基浪亚相在东海盆地宝云亭构造带为有利岩相带[144]。爆发相空落亚相在准噶尔盆地西北缘[141-142]、鸭绿江盆地长白坳陷[111]为有利岩相带。火山通道相火山颈亚相、侵出相内带亚相在松辽盆地可为有利相带[124]。火山沉积相含外碎屑火山沉积亚相在准噶尔盆地陆西地区[135]、海拉尔盆地贝尔凹陷苏德尔特构造带[136]、松辽盆地英台断陷和王府断陷为有利岩相带[89]。准噶尔盆地东部帐北断褶带[132]和西泉地区[145]、渤海湾盆地南堡凹陷 5 号构造的爆发相[146](未细划亚相)为有利相带;渤海海域基底火山岩爆发相与喷溢相(未细划亚相)为优质储层相带[147]。

4.4 火山地层单元与储层的关系

为了进一步明确火山岩储层空间分布规律,将岩性/岩相与储层关系扩展到三维地层范围,需要在火山地层单元的约束下进行储层分布规律的分析。火山地层基本单元常见熔岩流、熔岩穹丘、碎屑流和火山泥石流等[148-151],通过基本单元叠置构成了火山机构,火山机构的叠置形成了火山地层。基本单元中对于熔岩流和熔岩穹丘的储层分布特征研究较多,其他的单元还未见相关的分析成果;对于火山机构类型和相带的研究成果也较为丰富;基于火山地层的储层研究成果还有地层界面与储层的关系方面。笔者主要介绍了基本单元中的熔岩流和熔岩穹丘及火山机构类型-相带与储层的关系,地层界面与储层的关系见 4.5 节。

4.4.1 基本单元

(1) 熔岩流(lava flow)指从同一个喷出口(中心式或裂隙式均可)一次连续(宁静)喷发的熔浆形成的堆积体,通常冷凝固结成岩,岩石组构和地层产状呈连续变化,围限界面主要是喷发不整合或喷发整合[152]。如果按岩石成分也可划分为基性、中性和酸性熔岩流,按形态可划分为席状、板状、盾状、丘状和穹窿状等,按喷发环境可划分为水上和水下喷发。按叠置关系可划分为简单熔岩流和辫状熔岩流[153],以片状熔岩有序叠置为主时为简单熔岩流、以垛叶状熔岩交错无序叠置为主时为辫状熔岩流[图 6(a)—图 6(d)]。熔岩流垛叶体可以划分为顶部气孔带、中部致密带(或少气孔带)、底部管状气孔带。其中,顶部气孔带是熔岩流储层的主要分布位置,顶部气孔带的厚度变化较大,从 0.5～39.0 m 都有发现、占熔岩总厚度的比例为 6%～23%,孔隙度可高达 35%[130,151,154]。熔岩流广泛分布于准噶尔、三塘湖、松辽、二连和渤海湾等盆地,在基性、中性和酸性熔岩流中均有发现[131,140,155-157]。通过岩心和露头统计结果可知,松辽盆地和海拉尔盆地酸性熔岩流气孔发育在顶部 30 m 之内,基性熔岩流气孔发育在顶部 2～15 m。在细分熔岩流类型时,中基性辫状熔岩流的气孔层厚度与地层厚度的比值高于简单熔岩流[图 6(f)];简单熔岩流的气孔层在横向上具有较好的延伸性,辫状熔岩流的气孔层通过垛叶体的交错叠置可以形成网状的连通体[图 6(d)]。

(2) 熔岩穹丘(lava dome)又称"穹状火山"、"钟状火山"、"火山穹"、"熔岩锥"。由于熔浆黏性较大、流动性差,熔岩从溢出口挤出后向四周膨胀,并堆积在火山口附近,形成纵横比较大的穹窿状山丘[图 6(e)],常见安山岩、英安岩、流纹岩、粗面岩和响岩等。熔岩穹丘中不发育气孔,只发育冷凝收缩裂缝,如"似缝合线"和柱状节理等。松辽盆地徐家围子断陷粗面质熔岩穹丘储层厚度可达 70～200 m,储层占单元厚度的 7%～60%[图 6(f)][130];德惠断陷的英安质熔岩穹丘储层只分布在顶部,厚度约为 70 m,储层厚度与单元厚度比小[158];吉林省伊通盆地古近系玄武质穹丘揭示储层也只分布在顶部 60 m 范围。德惠断陷和伊通盆地熔岩穹丘平均孔隙度分别是 7.6%和 5.0%,熔岩穹丘的储层物性通常比熔岩流储层差。

4.4.2 火山机构与储层的关系

《地球科学大辞典》[159]将火山机构定义为火山作用的各种产物的总体组合,包括地面上的火山锥和岩浆在地下穿插形成的火山通道。考虑到地层产状变化规律与地层单元统一时,火山机构可定义为同一个主喷发口喷发的火山产物叠置而成的火山体或火山筑积

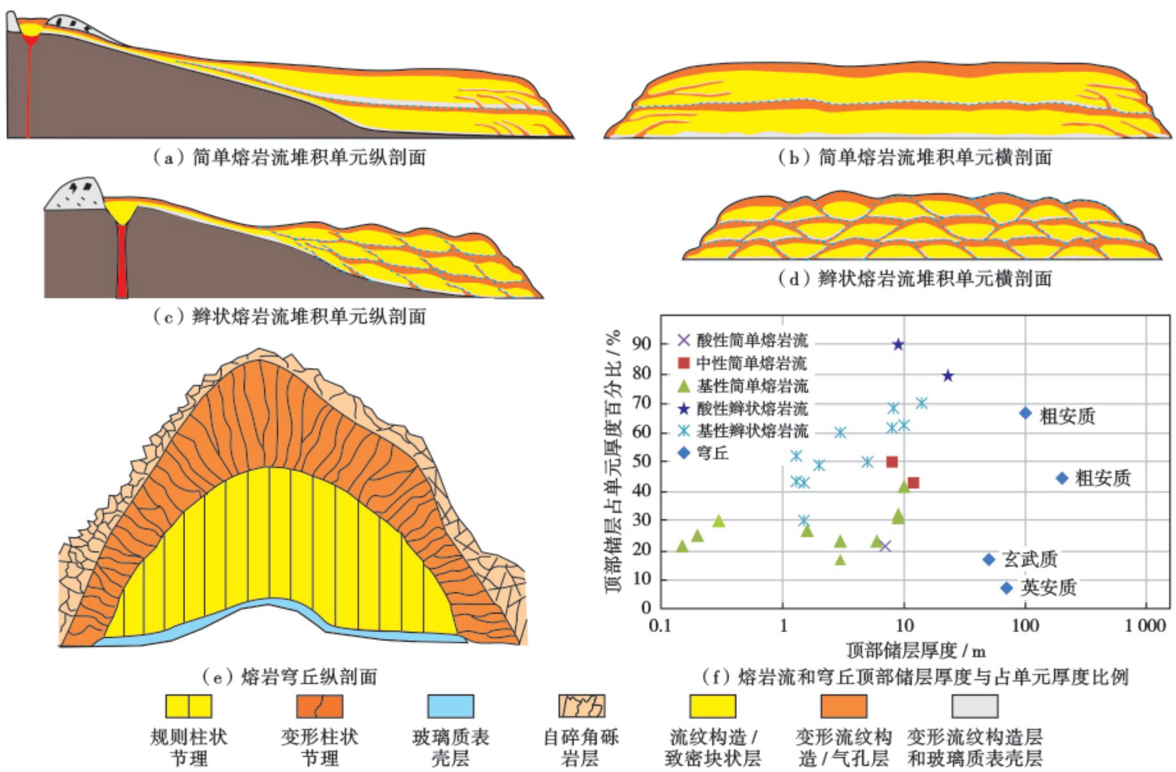


图 6　熔岩流和熔岩穹丘岩相模式及储层特征(据文献[151]修改)

Fig. 6　The facies architecture and reservoir characteristics of lava flow and the lava dome

物[152],其时间跨度可从数月至数十万年。火山机构主要由大型的喷发间断不整合界面围限,内部可存在小型(喷发)间断面。火山机构与储层关系的研究主要集中在类型、相带与储层的关系方面。

(1) 火山机构类型与储层的关系。火山机构按岩石构成比例可划分为熔岩、复合和碎屑型火山机构,按岩石化学成分可划分为基性、中性和酸性火山机构[160],按地层结构则可划分为似层状、层状和块状火山机构[161],按照外形可划分为盾状、丘状、锥状和穹窿状等火山机构[151]。在盆地内有钻井的情况下,可根据其岩石构成来划分火山机构类型。研究表明:酸性碎屑岩火山机构的储层厚度变化较小,其形态为板状或席状;酸性复合和熔岩火山机构气藏的储层厚度变化小,其形态为丘状和席状;中基性熔岩火山机构的储层厚度变化较大,其形态为丘状或楔状[160]。复杂岩性/岩相构成的火山机构比单一岩性/岩相火山机构的物性好[162]。

(2) 火山机构相带与储层的关系。虽然对火山机构相带的划分和命名上存在多种方案,但按岩性、岩相和地层产状特征的火山机构通常可划分为 3 个相带火山口-近火山口相带(中心相带)、近源相带(中部相带)和远源相带[87,163-164],各相带具有特定的组合特征(表 2):火山口-近火山口相带具有厚度大、地层倾角大、岩石叠置有序性差、碎屑颗粒大等特征;远源相带具有厚度小、地层倾角缓、岩石叠置有序性好、碎屑颗粒小的特征;近源相带的特征介于二者之间。储层质量与距离喷发中心的距离呈反比,距离近则孔隙度和渗透率值高、孔喉半径大、喉道分选好、中—粗歪度,距离远则孔隙度和渗透率值低、孔喉半径小、喉道分选为差—中等歪度[163][图 7(a)—图 7(f)]。从距墨西哥 Colima 火山喷发口 2.4 km、6.7 km、12.1 km 的中性熔岩、碎屑岩和再搬运火山碎屑等样品的孔隙度测试结果可知,随着离喷发中心距离的增加高孔隙度样品的数量显著减少[165][图 7(h)—图 7(j)]。钻井揭示火山机构中心相带是有利储层和油气藏富集的主要场所,普遍适用于松辽、海拉尔、准噶尔和渤海湾等盆地[166-170]。

4.5　喷发间断不整合/构造不整合界面与储层的关系

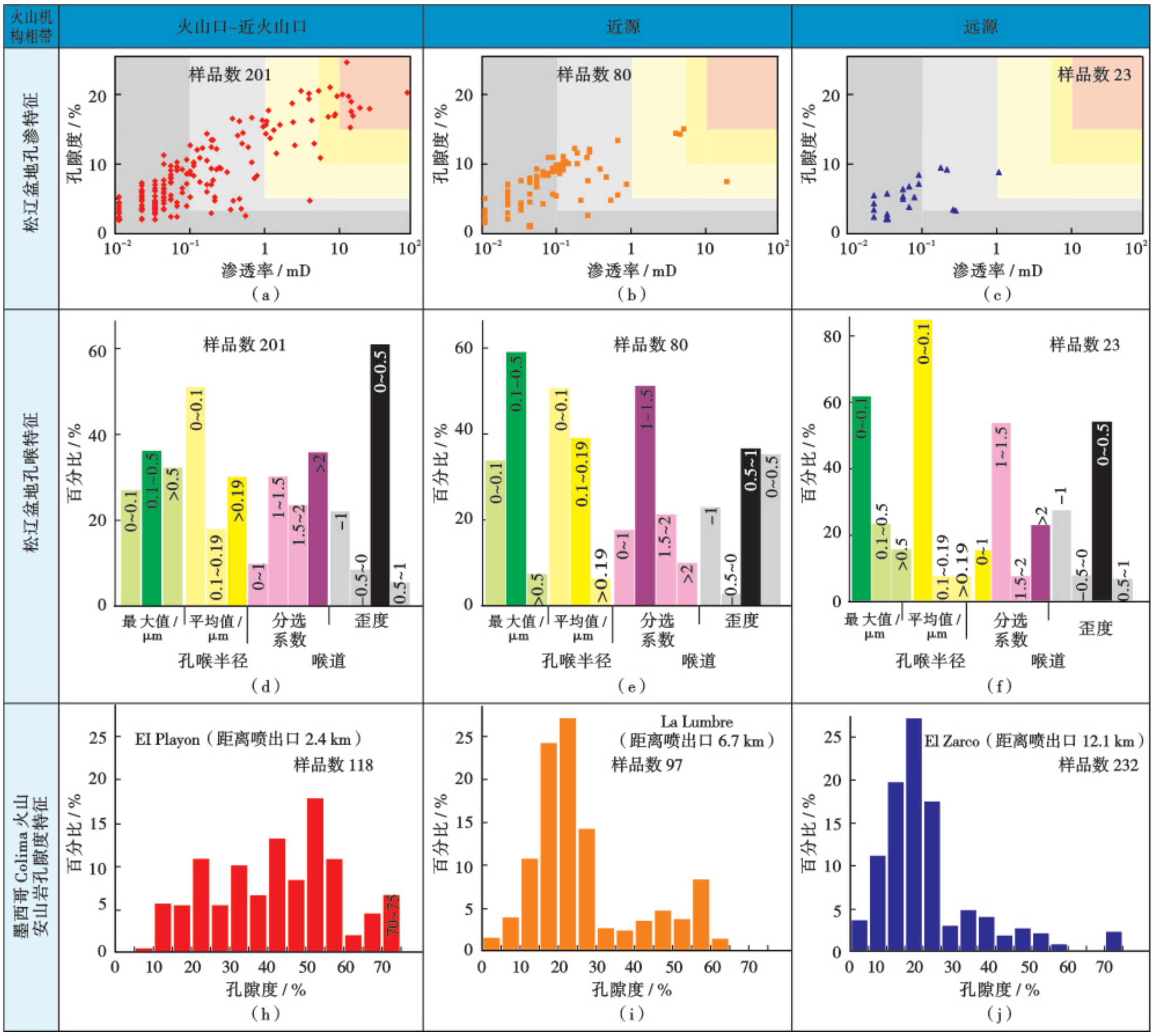
火山地层界面可划分为喷发整合、喷发不整合、喷发间断不整合和构造不整合界面[171-172]。火山岩的次生孔隙发育与流体通道关系密切,火山地层界面系统中喷发间断不整合界面和构造不整合界面可以指示暴露时开放体系流体作用区域和埋藏时流体通道位置,所以这两类界面与储层分布关系密切。喷发间断不整合界面指火山岩在经受喷发间歇期(一般为数十年至数千年)的侵蚀或剥蚀后与上覆火山岩形成的接触关系。该类界面在横向上存在风化壳(相对正地形)和

表 2　火山机构的相带和储层特征

Table 2　Characteristics of belts and reservoir of volcanic edifices

火山机构相带	特征岩石类型	特征岩石组构						特征岩相	地层单元类型	地层单元叠置	露头地层倾角/(°)	外形	主要储集空间						埋藏前风化	储层物性特征
		流纹构造	气孔杏仁构造	熔结结构	层理	碎屑粒度	其他						气孔/杏仁体内孔	粒间孔	溶蚀/溶解孔	隐爆缝	构造缝	脱玻化微孔		
火山口-近火山口	隐爆角砾岩、珍珠岩、枕状熔岩、(熔结)集块/角砾	高角度,强变形	圆状、椭圆状	强	块状层理	集块结构、角砾结构	隐爆角砾结构、岩球-岩枕构造、堆砌结构	火山通道相、侵出相	辫状熔岩流、简单熔岩流(厚层)、热碎屑流	杂乱无序	40～70(现今)/15～35(原始)	穹隆状、丘状和盾状	发育	大孔	铸模孔、筛状孔、微孔	发育	环状—放射状缝,密度大	无明显差别	强	中孔高渗储层、局部为高孔高渗储层,孔喉半径大、分选好
近源	(熔结)角砾\凝灰岩、熔岩	中—低角度,弱变形	管状、椭圆状、圆状	弱	波状层理、块状层理、粒序层理、交错层理	角砾结构、凝灰结构		喷溢相、爆发相热碎屑流和热基浪亚相	简单熔岩流(薄层)、热基浪、碎屑崩塌堆积	杂乱无序—有序	30～45(现今)/5～25(原始)	楔状和板状	少量	中孔	筛状孔、微孔	少量	密度中等		中	中孔中渗储层、局部为中孔高渗,孔喉半径较大、分选较好
远源	沉火山碎屑岩、凝灰岩、玻质碎屑岩	少量熔岩	少量气孔	无	水平层理、平行层理	凝灰结构、碎屑结构		火山沉积相和爆发相空落亚相	空落、火山碎屑裙、火山泥石流	有序	25～30(现今)/0～5(原始)	板状和席状	微量	小孔	微孔	无	规则应力缝,密度小		弱	中—低孔低渗储层,孔喉半径小、分选差

注:据文献[151,163]修改整理,资料主要基于东北地区盆地内和盆缘中生代—新生代火山岩。



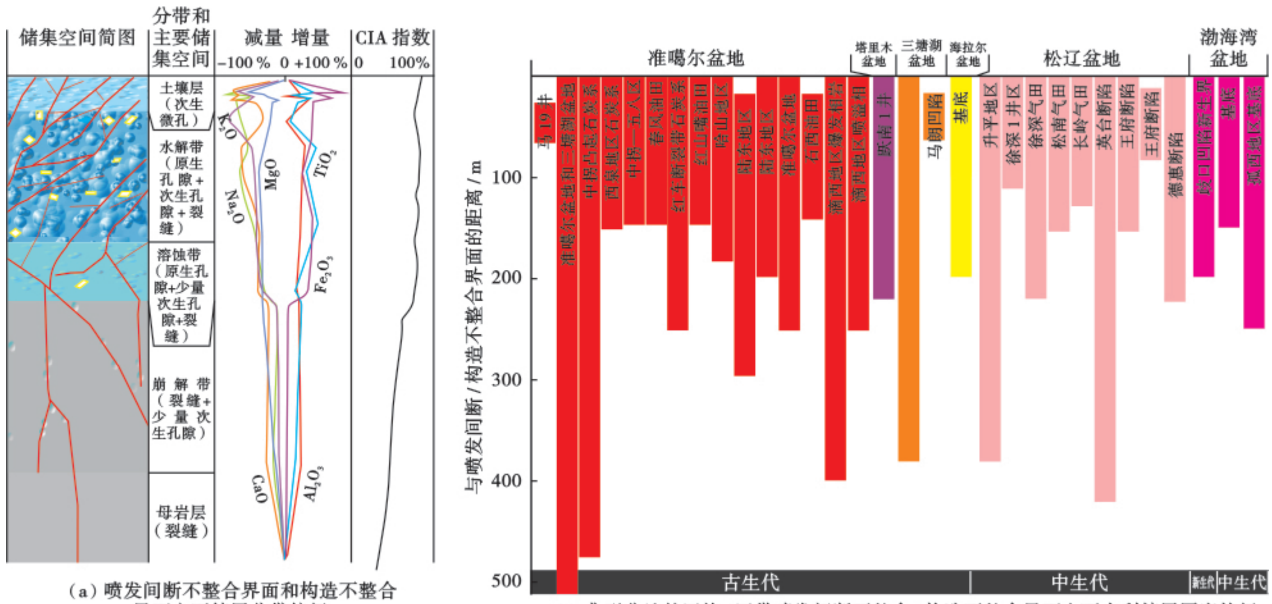
注:松辽盆地白垩系火山岩资料据文献[163],墨西哥 Colima 火山 2013 年喷发物资料据文献[165]。

图 7　火山机构相带与储层物性的关系

Fig.7　Relationship between the volcanic edifices belt and reservoir properties

含下伏岩层碎屑的火山岩/沉积岩（相对负地形）的组合特征。构造不整合界面指以盆地或次级构造单元范围内的火山岩经历整体抬升剥蚀或差异埋藏后与上覆岩层间形成的接触关系。当构造抬升时，火山岩经受长期剥蚀夷平作用，发育分布范围广、形态较为平整的风化壳。风化壳与沉积岩层规模往往大于喷发间断不整合。喷发间断不整合和构造不整合界面之下的风化壳具有分层性[图 8(a)]，自上而下可划分为土壤层、水解带、溶蚀带、崩解带和母岩层，其中，水解带和溶蚀带中的孔隙最为发育。

钻井揭示多数有利储层分布于喷发间断不整合和构造不整合界面之下的 200 m 范围内、少数情况可延伸到 500 m 的范围。不同盆地之间该范围值存在差异，同一盆地不同区块的范围值也不同，同一区块不同井之间也存在一些差别[图 8(b)]。研究表明，准噶尔、海拉尔和松辽等盆地的喷发间断不整合和构造不整合界面之下的有利储层具有分带性[173-176]。有利储层的厚度和垂向分布范围受多种因素控制，如风化壳的古地貌分带、残丘及其边缘地带要好于缓坡带、更好于沟槽带和洼地带[177]；岩性/岩相特征也是影响储层分布范围的重要因素，如准噶尔盆地滴西地区石炭系构造不整合界面之下为爆发相岩石时可延伸到界面之下 400 m、为喷溢相岩石时可延伸到界面之下 250 m[178]；断裂带的存在也可使风化作用影响的深度范围变大[63]。



（a）喷发间断不整合界面和构造不整合界面之下储层分带特征

（b）典型盆地的区块/区带喷发间断不整合/构造不整合界面之下有利储层厚度特征

注：$CIA=\{(Al_2O_3)/[(Al_2O_3)+(CaO^*)+(Na_2O)+(K_2O)]\}\times100\%$，主成分均指摩尔分数，$CaO^*$ 仅为硅酸盐中的 CaO；图(b)中的数据来源于文献[63,128,145,147,170,173-174,177-185]。

图 8 喷发间断不整合-构造不整合界面与储层的关系

Fig. 8 Relationship between the eruptive interval unconformity boundary-tectonic unconformity boundary and reservoir in the volcanic rocks

有利储层的发育也促进了油气聚集。从钻井揭示的情况来看，多数油层/气层/气水层/油水层在喷发间断不整合和构造不整合界面之下 150 m 范围以内[图 9(a)和图 9(b)]，油层/气层/油气同层更多的是集中在 100 m 范围之内[图 9(c)]，该深度段应该是油气勘探的重要层位。

5 储层形成机理

对储层起建设作用的主要有原生的挥发分逸出、冷凝收缩、炸裂和碎屑颗粒支撑作用等，以及次生的重结晶、构造改造、大气水-地层水-深部热液的溶蚀/溶解作用等[46,188-191]；对储层起到破坏作用的主要是充填、压实和胶结作用[57,192]，笔者主要介绍对储层起建设作用的成岩作用。

5.1 挥发分逸出作用

在熔浆从岩浆房向上运移时，熔浆含有挥发分，如水、二氧化碳、氟和氯等组分[193-194]，还可含少量的 He 或 Ar 等[195]。在岩浆压力下降时从熔浆中逸出产生气泡；并随熔浆向上迁移发生膨胀—合并[196]，气泡被固化的熔浆捕获，形成气孔。挥发分逸出主要可以划分为两个阶段，分别为火山通道中上升过程和喷出地表后流动过程。前者可以看作近似等温降压过程，是气孔形成的主要阶段；后者为近似等压降温过程，气孔只比前一阶段在形状和分布方面进行调整，基本不再产生新的气孔。

挥发分逸出作用产生的气孔通常会聚集在熔岩流的顶部，通常玄武质熔岩流厚度超过 3 m时该现象就

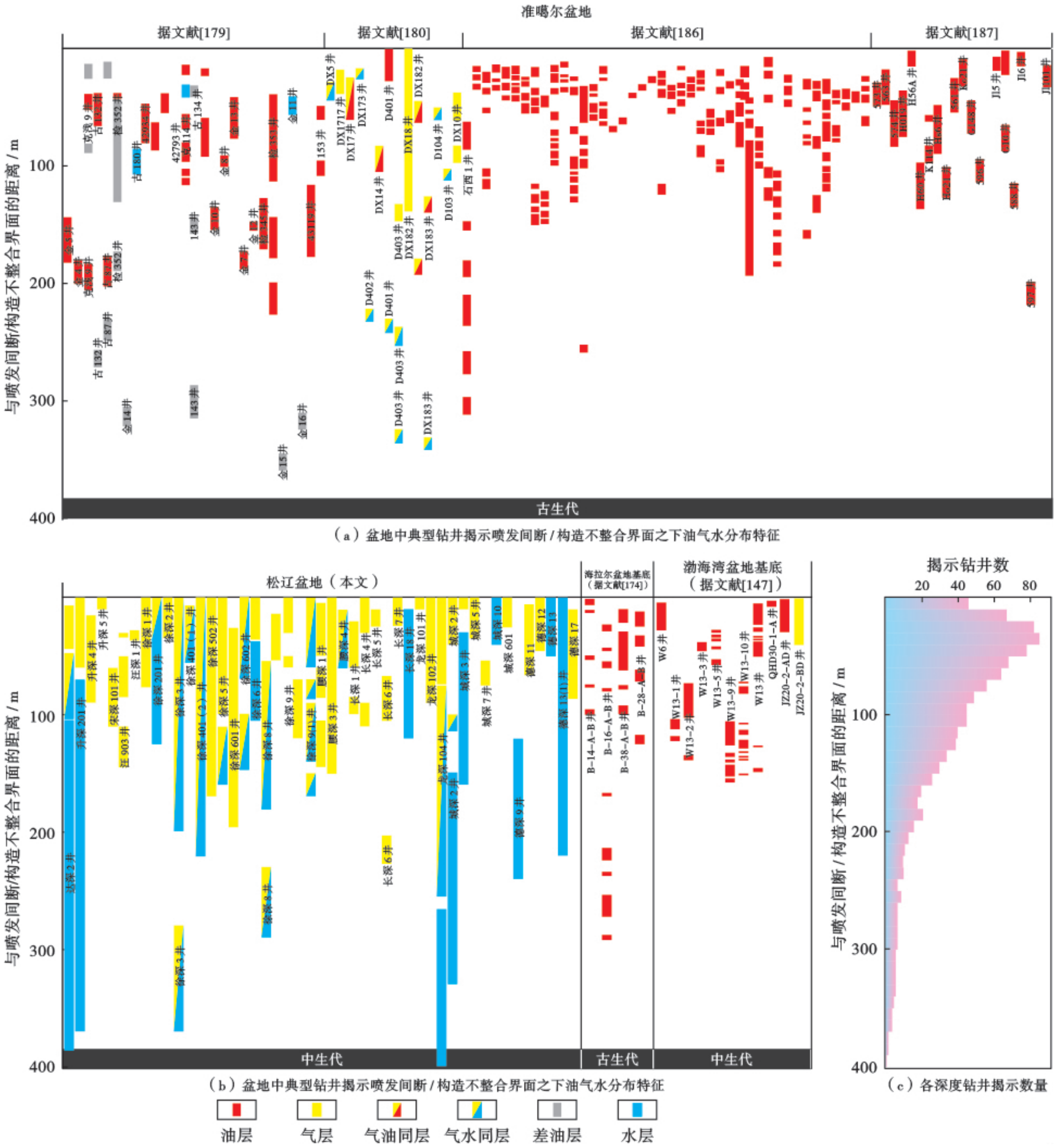


图 9　喷发间断不整合-构造不整合界面与油气层分布的关系(据文献[147,174,179-180,186-187]整理)

Fig. 9　Relationship between the eruptive interval unconformity boundary-tectonic unconformity boundary and oil-gas distribution

变得十分明显[197],可促使熔岩流中形成上部好、下部差的储层模式。此外,当熔浆流经湿环境区域时,熔浆可捕获外来的水而形成气孔[198];该现象在松辽盆地王府断陷的火石岭组薄层流纹岩中揭示,形成该区域熔岩流储层物性底部好上部差的特殊模式[199]。五大连池火烧山区域的喷气锥就可能是该成因[200]。当气孔接受充填时会变成杏仁构造,该现象在基性岩中更常见。在松辽盆地玄武岩中的杏仁体可见单成分和复成分两种类型,单成分充填是储层变差的标志,复成分可看作为储层改善的标志[201],因为原本孤立的气孔变成连通系统,流体进入才可形成复成分杏仁体。

气孔形成符合合并—扩散—减压模型,浮岩中的气孔数量密度与气孔体积之间呈非线性反比关系[202]。原生气孔的发育与熔浆挥发分密切相关,流纹岩在岩浆含水量低时含水率的变化会引起气孔数量的剧烈变化[203];气泡大小、形状和分布对渗透率影响明显[204];气孔类岩石孔隙度越大、抗压强度就越小,气孔直径越大、抗压强度就越小[205]。

5.2 冷凝收缩作用

冷凝收缩作用通常指熔浆在上升和地表溢流的降温过程中，熔浆与相对低温的围岩、空气和水体接触冷却的过程，由于熔浆在固化阶段是降温阶段，体积会收缩变小，产生张性应力，可以形成裂缝。裂缝的形成与冷却速度关系密切，如熔岩流在快速流动过程中（冷却速度中等）可能在顶部产生自碎角砾缝，在底部产生层状节理，当熔岩流的流动速度减缓时（冷却速度慢）可能产生贯穿熔岩流的高角度宏观龟裂缝和不规则微小龟裂缝的组合[206]，当熔岩停止流动时，厚层熔岩流会形成下部规则和上部变形柱状节理的组合。如果熔岩流与较深水体接触时（冷却速度快速、也称作为淬火作用）会产生枕状构造，并在岩枕内部发育放射状、环状节理[207]。盆地内常见水下喷发火山岩，如准噶尔盆地和三塘湖盆地晚古生代火山活动具有水下喷发的特征[208-209]，该地区的熔岩流应该会存在该类裂缝。松辽盆地常见的珍珠岩/松脂岩/黑耀岩穹窿就发育枕状构造，该类岩石具有较好的储集性能[137]。此外王府断陷火石岭组位于浅湖环境的流纹岩底部发育淬火缝[199]。特殊的位置也可产生一些特殊裂缝，如在熔岩管道里可形成柱状节理、环状节理和放射状节理等裂缝的组合[153,210]。

5.3 炸裂作用

炸裂作用有3种：①熔浆在上升过程中压力降低的膨胀过程使得斑晶破碎；②由于挥发分逸出，但气泡膨胀受阻，其膨胀力高于基岩骨架拉伸强度时发生炸裂；③富含挥发分的熔浆在浅地表发生的爆炸作用。第1种方式可使熔浆中脆性体（通常为晶体）破碎，如石英中可见不规则的缝面[图3(e)]，再如沿着长石、角闪石和辉石等晶体的解理裂开成缝、叠加少量与节理面斜交的不规则裂缝。第2种方式可产生大量的火山碎屑，碎屑中保留一部分炸裂缝。第3种隐爆作用使围岩发生破碎，形成树杈状裂缝[图3(m)]，在松辽盆地和辽河盆地中可形成有效储层[35]。

5.4 颗粒支撑作用

当熔浆经受了炸裂作用后产生火山碎屑，火山碎屑按粒径可划分为集块、角砾和凝灰[211]。多数情况下喷发中心区域火山碎屑具有棱角状、分选差、杂乱堆积的特点，远离喷发中心区域的颗粒为次棱角状—棱角状、分选为中等—好、层理发育。相对粗的火山碎屑颗粒可形成稳定的骨架，骨架的形成对于储层的形成具有两方面的作用。首先是在支架之中未充填或低充填程度时可形成粒间孔；其次是由于颗粒支架的支撑作用，减少压实作用对粒间孔和基质溶蚀孔的破坏[212]。对于支撑作用，熔岩岩屑应好于火山碎屑岩的岩屑，因为火山碎屑岩的岩屑含有火山灰，火山灰遇水会软化。火山碎屑岩被埋藏时，颗粒格架起到保护粒间孔的作用，当上覆静压力逐渐增大时颗粒的接触关系由点接触向线接触转变，粒间孔就遭受严重的破坏。支撑作用可能在浅层能发挥较大的作用，而到了深埋藏阶段时作用有限。

如图3(d)所示的颗粒间存在点—线接触表明遭受了机械压实，幸运地是，存在一些抗压颗粒支撑形成骨架保护了基质中的粒间-溶蚀孔，通过分析孔隙图像可知其面孔率高达20.8%。同样，在机械压实作用更强的线—凹凸接触岩石中，残余粒间孔的面孔率为1.8%～5.0%[89]。因此，颗粒支撑作用对于沉火山碎屑岩具有重要的保存孔隙作用，存在内凹边缘的颗粒可以发挥更好的保护作用。

5.5 构造作用

在构造应力作用下产生构造裂缝，致密的熔岩、碎屑熔岩和火山碎屑岩中均可以发育这类裂缝。通常受剪切构造应力作用产生高角度、缝面平直、延伸远、具有方向和组系的剪切裂缝；常可见共轭节理，在地层发育褶皱时，可发育平行于轴面的劈理，准噶尔盆地、三塘湖盆地和塔里木盆地广泛发育大型逆冲构造带、该类裂缝也大量发育，海西运动期是裂缝的主要形成时期[213]。松辽盆地、海拉尔盆地发育晚白垩世反转构造带，也可形成类似的裂缝。辽河盆地和渤海湾盆地发育中生代—新生代走滑断裂系，也可形成张扭性裂缝。在张性构造应力下岩石发生破碎形成网状、不规则、连通性好的张性构造缝；中国东部盆地的断陷期可以促进该类裂缝的形成，在应力扰动作用明显的断层上盘裂缝较发育[168]，裂缝的线密度与距离主干断裂的距离呈反比关系，对油气成藏也有一定的约束作用[214]。

5.6 风化作用

风化作用有物理风化和化学风化两种，二者均可在已有的连通孔缝系统基础上增加次生孔缝系统，使储集性能得到提高。物理风化表现为受温度变化影响和外力作用使岩石产生裂缝，风化壳之下的裂缝发育带范围与有利储层发育带具有相似性，裂缝发育带可延伸到界面之下250 m的范围[181,215]。化学风化多表现为淋滤作用，主要是大气降水、湖水或海水的溶蚀/溶解作用，风化淋滤作用可形成大的晶内溶孔、铸模孔、基质中网状的溶孔-裂缝系统等[182,216]。在物理风化和化学风化的作用下形成的风化壳，根据风化产物的特征可划分为最终分解产物带、水解带、淋滤带、崩解带、未风化带（母岩）5个带；基性岩风化壳的最终分解带多是黏土矿物和碳酸盐矿物；水解带中橄榄石伊

丁石化、斜长石高岭土化、辉石绿泥石化等；淋滤带的矿物变化类似于水解带，但风化程度较弱；崩解带以物理风化为主。从物质组成来看大致可与三塘湖盆地石炭系卡拉岗组风化壳的土壤层、水解带、溶蚀带、崩解带、母岩层相对应[63,183]。风化壳型储层主要分布于溶蚀带（淋滤带）。

风化作用在火山地层中十分常见。由于火山地层具有建造时间短、改造时间长的特点，在短时间内的大量喷出物堆积在有限的范围内必然会形成一个局部凸起，特别是在火山口附近可形成高约数百米的正地形，上覆沉积地层要覆盖火山岩可能需要数百万年的时间，所以通常火山在埋藏前都要先遭受一定时间的风化作用，如王府断陷火石岭组粗安质火山地层经受埋藏前风化淋滤的最长时间可达 35 Ma[128]。熔岩可有效保存该阶段形成的溶蚀孔，这是火山岩储层形成与沉积岩相比的显著差别因素之一。再者火山地层埋藏后受构造抬升影响会出露地表，遭受风化淋滤作用，如准噶尔和三塘湖盆地的石炭系—二叠系火山岩可能经历一次埋藏后再抬升风化淋滤作用[184,217]；渤海湾盆地中生代—新生代火山岩均可能经受相似过程[147,218]。风化淋滤能影响的地层厚度，与所处的古地貌位置以及下伏岩石组构密切相关，如在古地形高部位影响更深，下伏地层原生孔缝发育的区域也可影响更深[177-178,219]。

5.7　埋藏溶蚀/溶解作用

埋藏溶蚀/溶解作用需要两方面的物质基础，一是流体、二是易溶蚀成分。流体可存在酸性和碱性两类，分别对应不同的易溶蚀成分。多数盆地以酸性流体为主，少数情况下也出现碱性流体。通常淡水—半咸水沉积地层和含煤地层在埋藏过程中会产生富有机酸和碳酸的流体；此外，酸性流体还可能来源于无机成因的 CO_2，如松辽盆地火山岩储层孔缝中充填的方解石记录了无机成因 CO_2 来源[220-221]。三塘湖盆地马朗凹陷卡拉岗组火山岩中发生了浊沸石充填和石英溶解，可知该区域经历过碱性流体的作用[222]。

断陷盆地地层中常发育暗色泥岩和煤层，按照煤的形成过程可知有两个阶段会产生大量的有机酸：①在埋深 200～400 m 范围内的植物遗体转化为泥炭、再到褐煤的过程，流体的 pH 值可达 3.3～4.6[223]。②当地温达到 80～120 ℃时，随着泥岩和煤层有机质演化排出有机酸性物质，地层水 pH 值明显降低，酸性条件下易溶成分可再次发生溶蚀/溶解作用[224]；当超过 120 ℃时还可产生大量的碳酸。火山岩中发育大量酸性条件下易溶成分，如橄榄石、辉石、角闪石、碱性长石、岩屑、玻璃质成分和火山灰等，其总含量远远高于普通的长石砂岩、岩屑砂岩和石英砂岩等[169,225]；还可包括早期碱性条件下析出的浊沸石和方解石等[226-229]或者是在风化过程中斜长石蚀变成浊沸石等[217]。埋藏溶蚀/溶解作用可产生溶蚀筛状孔和微孔[230-232]，还可促进火山岩风化壳内内幕型储层的形成[233]或者改善喷发间断不整合界面之下的储层物性。溶蚀/溶解特征可以根据中子孔隙度、实测地层电阻率、密度测井计算的孔隙度等参数来定义；蚀变储层的岩性指数较小、蚀变指数较大，未蚀变储层的岩性指数较大、蚀变指数较小[234]。

5.8　脱玻化作用

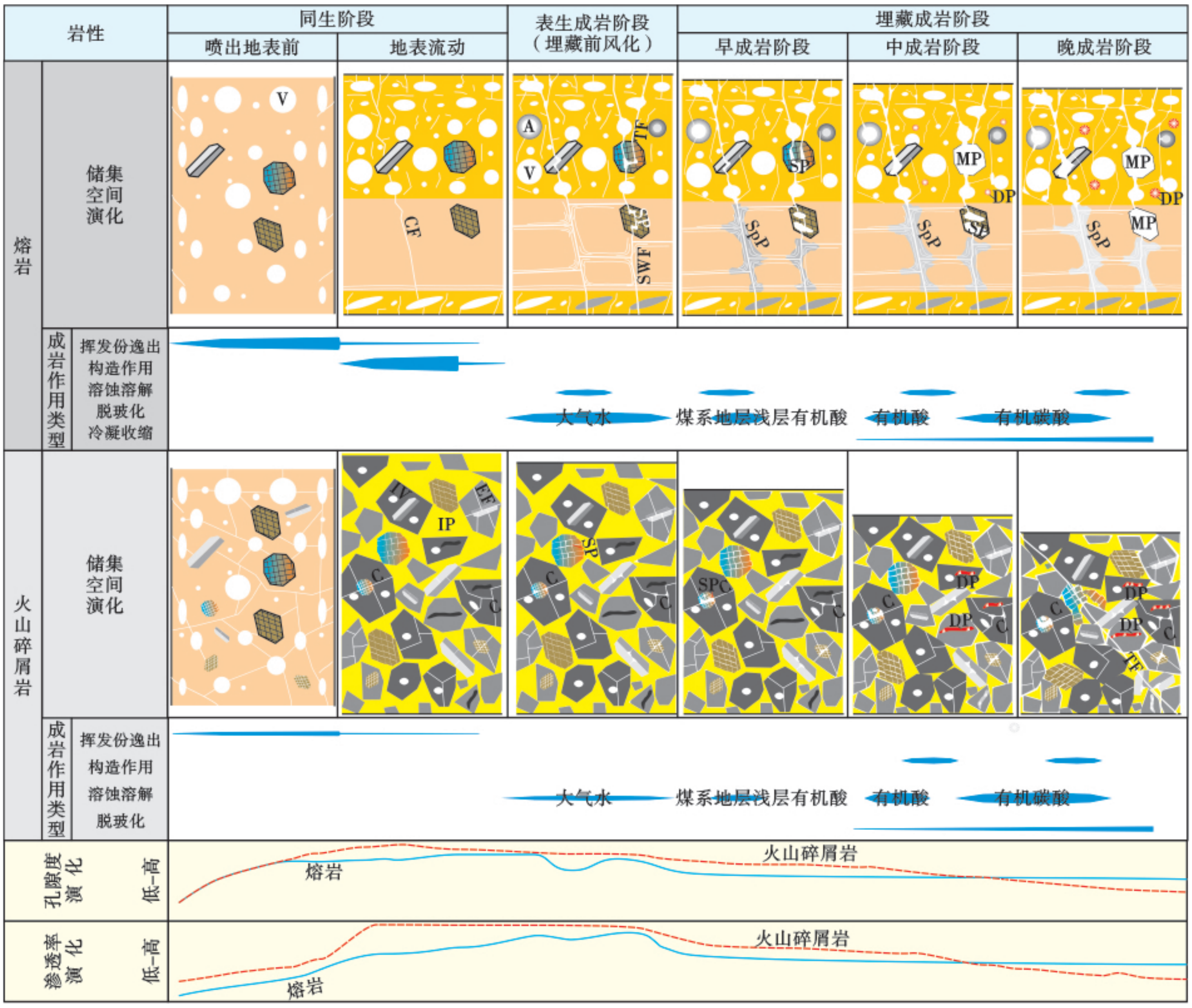
脱玻化作用又称脱玻作用、失透作用、晶化作用。火山岩中玻璃质成分是不稳定的，埋藏使温度、压力升高，玻璃质将逐渐转化为结晶物质，即产生脱玻化作用。酸性玻璃脱玻后，常具霏细结构和球粒结构[图 3(q)]，析出高价氧化铁。基性玻璃脱玻后多为隐晶质结构，析出高价氧化铁。运用火山玻璃脱玻化作用的物理过程及质量平衡的原理和方法，可估算球粒流纹岩、熔结凝灰岩、凝灰岩中流纹质玻璃脱玻化作用产生的孔隙，结果表明流纹质玻璃完全脱玻化形成长石、石英球粒，可产生≥8.88％的孔隙度[125]，如在徐深 1 井中脱玻化作用可使流纹岩孔隙度增加 2％～5％[235]。脱玻化作用的重要意义在于不需要原生孔隙沟通流体来产生溶蚀孔，岩石自身可产生连通的次生储集空间，这也是火山岩储层独有的现象。该类孔隙在露头区就有发现，储层品质好并充填原油[236-238]，具有良好的勘探指示意义。

5.9　多成因的复杂叠加结果

火山岩储层的形成是上述多因素的综合结果，大体上可以划分为同喷发期原生孔隙形成阶段、埋藏前风化阶段、埋藏溶蚀阶段[239-243]。伴随热液充填（同喷发期火山热液和后期构造-热事件热液）的改造，有的区域还经受埋藏后抬升剥蚀、再埋藏的过程[244-246]，使储集空间的演化过程更加复杂化。先形成的原生孔隙、裂缝和构造裂缝为后期流体作用于岩石提供通道，控制着次生孔隙的发育[247-249]。其中，裂缝对大孔大缝型储层的形成起着重要的作用[185]，高角度裂缝带可能控制着有利区储层的垂向分带性[250]。

火山岩中储集空间类型的演化可分成冷凝固结成岩的熔岩和压实固结成岩的火山碎屑岩两类。二者的演化过程存在一定的差别，其中，熔岩受压实变形较小、火山碎屑岩的变形大。因此，熔岩中的气孔随埋深的增大时直径可能有少量的减少，而数量和形态基本保持不变，溶蚀产生的铸模孔、筛状孔等也容易得以保存。当火山碎屑岩埋深增大时，颗粒支撑型岩石的颗

粒接触方式为点—线—凹凸接触，部分颗粒可能会破碎，颗粒之间由于应力的变化可能还会产生位移来达到新的支撑平衡，所以火山碎屑岩的粒间孔直径会显著变小，数量可能会有小幅度的增加。早期产生的溶蚀孔隙在颗粒的支撑调整过程中可能大量损失、难以保存，对储层的贡献有限(图 10)。



注：A—杏仁体内孔；DP—脱玻化微孔；IP—粒间孔；SpP—海绵状溶蚀孔；SP—筛状溶蚀孔；MP—铸模孔；V—气孔；C—炸裂缝；CF—冷凝收缩缝；TF—构造缝；SWF—球状风化缝。

图 10　火山岩孔隙演化模式

Fig. 10　Evolution model of pore in volcanic rocks

6　存在问题和研究展望

通过目前的研究成果进行总结和讨论，下一步亟需开展的深化研究工作包括、但不限于以下几个方面。

6. 1　火山岩地层单元的储层原型模型

目前发现火山岩储层受岩性、岩相、火山机构、火山地层界面、地层结构和成岩作用等因素影响，在一定程度上推动了火山岩储层分布规律的认识。但当遇到未揭示过的地层单元类型时，储层预测结果与实际情况相差较远，如储层发育部位、层数、厚度等均不准确。由于缺乏从地层成因和地层单元角度入手的储层分布规律认识，难以达成储层分布规律的全面认识，多数情况更像是“盲人摸象”。在现有资料约束下刻画完一个油气藏时可能觉得储层分布规律清晰，但在下一口钻井揭示后发现，已有的分布规律可能不适用，犹如大象躯体的各个器官中，对耳朵的认识不适合对其他器官的认识。所以对每个火山岩油气藏的认识均是“摸着石头过河”，需要大量的重复性工作才能完成油气藏的储层刻画。

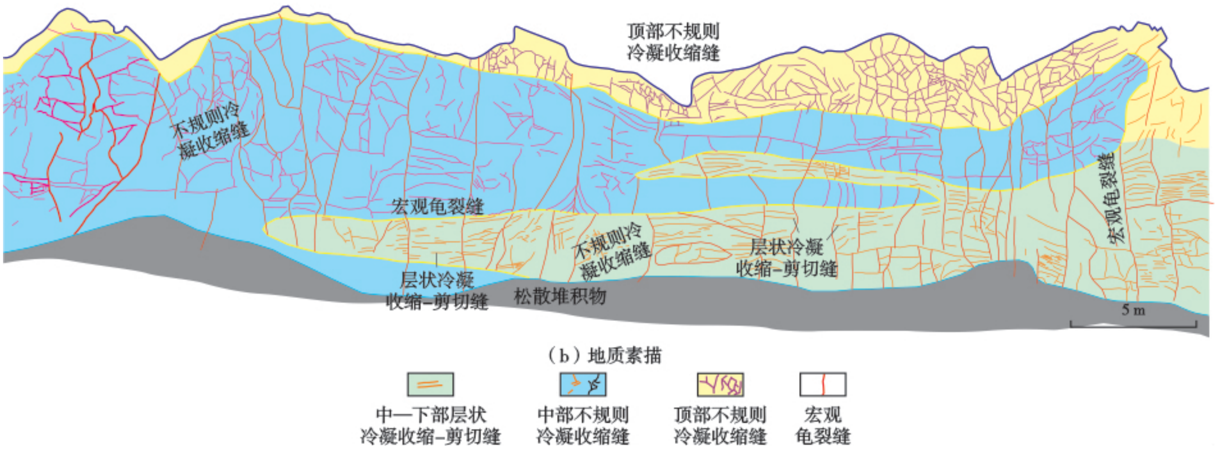
为了解决该类问题，应该基于火山地层基本单元的储层原型模型分析。只有清楚认识所有基本岩石地层单位的储层分布规律，才能对火山地层储层分布规律进行全面认识，为提高储层刻画效率提供依据，使储层研究成果可以有的放矢地指导盆地火山岩油气勘

探。目前，对于陆上熔岩流单元和熔岩丘单元的储层模式较为清晰，其他的碎屑流、（热）基浪、火山泥石流、碎屑裙、崩塌和水下熔岩流等单元的储层模式还缺少三维量化的认识，需要加强上述各类地层单元的储层原型模型研究。如水下喷发的火山与陆上喷发的火山地层单元的相结构存在显著的差别，该类单元在准噶尔、三塘湖、辽河和松辽等盆地都广泛发育[208-209]，所以建立起相关的原型模式既是实践的需求，也是火山岩储层地质研究进步的需要。

6.2　熔岩流裂缝的表征

裂缝是火山岩储层的重要组成部分，也获得了学者们的一定关注[53,168,181,251]。如已认识到喷发阶段对微裂缝的形成具有至关重要的作用，大量的裂缝可形成于熔浆冷却阶段[252]；在熔浆流动过程中由于冷却造成流速的差异，在熔岩流边缘部位可以产生垂直于流动方面的微裂缝，使得气孔间存在连通的通道[253]，同时也使熔岩流存在良好的通道系统（图 11）。高孔隙度样品含有微裂缝时，对岩石的渗透性改善不明显[254]。低孔隙度样品中含有微裂缝时，渗透率往往能高出基质部分 3～4 个数量级，但该部分微裂缝对于整个火山地层来讲，可能渗透性有限[255]。因此，如何从样品尺度扩展到整个地层尺度、即如何将野外/岩心观测结果、实验室测试结果与测井解释结果、地震预测结果进行匹配也值得深入分析。同时，在埋藏火山岩的裂缝描述中，第一手资料是岩心，受其取心率和揭示的局限性，难以实现对裂缝的全面认识，应当加强原型模型的刻画；在原生裂缝形成过程、原生裂缝发育的控制因素的量化刻画方面也需要加强研究。

（a）野外剖面



（b）地质素描

图 11　新西兰 Ruapehu 火山更新统 Whakapapa Iwikau 组安山质熔岩流裂缝系统

Fig. 11　Fracture system of andesitic lava flow of Pleistocene Whakapapa Iwikau Formation in Ruapehu Volcano, New Zealand

6.3　储层成因的定量研究

从火山岩的储集空间、储层物性、分布规律和形成机理来看，储集空间类型和储层物性的研究已基本明确，储层分布规律也认识较为全面、可有效地指导勘探开发[256-260]，但储层形成演化的研究进展远落后于上述 3 个方面。目前，对储层分布规律、成因和主控因素的分析还只是各种因素综合效应的表述，严重阻碍了对火山岩储层地质理论的深入认识。盆地火山岩储层形成和演化可以分为岩浆上升-喷发阶段和喷发后-埋藏阶段。前者是控制原生储层发育的主要阶段，挥发分含量高的熔浆缓慢上升脱气就可能形成喷溢相，反之快速上升则可能形成爆发相[261]，挥发分含量低的黏稠熔浆由于表面张力的作用使熔浆加速固化避免了爆炸式喷发[262]，现代火山揭示原生孔隙的连通性与岩性和喷发方式相关[263]；后者是原生储层改造和次生储层形成的主要阶段。对于第 1 阶段的储层演化研

究应该还处于初期阶段,这主要也是受限于实验条件的影响。第 2 阶段的储层演化研究进展较第 1 阶段深入,但也主要是定性的分析。主要原因是当原生和次生孔隙叠加时,准确地将二者贡献度分开变得十分困难,或者是几乎不可能;同时也缺少岩石成岩方面的实验和模拟;再者众多原因的叠加导致了火山岩储层成因和演化分析难以达到量化表征的阶段。但是为了明确火山岩储层的主控因素,开展储层成因定量刻画是十分必要的。如风化壳型储层的刻画,需要定量或半定量地将各成因形成的孔隙的贡献计算出来,才能明确风化淋滤作用真实的影响范围;再如压实作用对熔岩和火山碎屑岩的孔隙演化的量化描述。

7 结 论

(1) 火山岩中可识别出 11 类 28 型孔隙,其中,原生孔 3 类 5 型、原生缝 2 类 9 型、次生孔 3 类 8 型和次生缝 3 类 6 型。原生孔隙与相结构密切相关,次生孔隙与原生孔隙和裂缝等相关。火山岩储层整体上属于中—低孔、中—低渗储层,也可称作致密储层,火山岩储层非均质性强、物性下限较低,不同的储集空间类型组合对孔隙度和渗透率关系影响显著。

(2) 储层分布受埋深影响,在 3 km 之上火山碎屑岩具有优势,在 3 km 之下熔岩具有优势。总体来看,各种岩性均有机会发育成有利储层,但在具体的区块中只能有特定的岩性成为有利岩性;岩相中有 5 相 7 亚相可成为有利相带,即火山通道相火山颈亚相、爆发相热碎屑流亚相/空落亚相、喷溢相上部亚相、侵出相内带亚相、火山沉积相含外碎屑火山沉积亚相;储层分布模式受火山地层单元约束,如熔岩流垛叶体和熔岩穹丘形成"上好下差"的模式,熔岩流储层物性高于熔岩穹丘;火山机构的中心相带储层物性好于近源相带、远源相带最差,该规律普遍适用于各盆地的各类火山机构中。多数有利储层分布在喷发间断不整合界面或构造不整合界面之下的 200 m 范围之内。

(3) 对储层起到建设作用的主要有原生阶段的挥发分逸出、冷凝收缩、炸裂和颗粒支撑等作用,以及次生阶段的重结晶、构造改造、大气水-地层水-深部热液的溶蚀/溶解等作用。盆地火山岩储层是上述各类成岩作用综合的结果,具有复杂的形成过程,特别是火山地层经受了多次抬升和埋藏时,其风化淋滤和深埋藏溶蚀/溶解的演化过程更加复杂化。挥发分逸出、冷凝收缩、埋藏前风化、脱玻化等作用是火山岩所特有的成岩作用类型。埋藏前风化作用多发生在火山机构的中心部分,促进了中心相带次生孔隙的发育。火山岩中—高含量酸性条件下易溶成分可提供溶蚀/溶解的物质基础,有利于次生孔隙的形成。

(4) 熔岩随埋深的增大其形态基本保持不变,有利于原生气孔、次生铸模孔、次生筛状孔等得以保存。火山碎屑岩在埋深增大时,颗粒之间由于应力的增加可能还会产生位移或破碎来达到新的支撑平衡,粒间孔直径会显著变小,数量可能会有小幅度的增加;风化和浅埋藏阶段产生的溶蚀孔隙在颗粒的支撑调整中可能大量损失、难以保存。

(5) 火山岩储层地质研究方面,在完善火山地层单元的原型模型、储层成因刻画方面还需要加强研究。首先是火山岩储层特殊的岩浆上升过程和喷发过程对于原生孔缝的形成过程及原生孔隙的控制因素分析还需要加强;其次是开展次生孔隙演化的单因素量化分析,如压实、风化、胶结等作用。

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